Daniel, Professor H. Schopper, and Professor G. Weber, and the staffs of the Wilson Synchrotron Laboratory and DESY.

[(a)]Now at Carnegie-Mellon University, Pittsburgh, Penn. 15213.

[(b)]Now at Beiersdorf AG, Hamburg, Germany.

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Yang's Parity Test for the New Spin-0 Mesons

Ngee-Pong Chang
Physics Department, City College of the City University of New York, New York, New York 10031

and

C. A. Nelson
Department of Physics, State University of New York at Binghamton, Binghamton, New York 13901
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Yang's parity test for general spin-0 mesons applied to the decay sequence $X \to \varphi\varphi \to (K^+K^-)(K^+K^-)$ leads to maximal parity signature. The correlation function for the azimuthal angle between the two $\varphi \to K^+K^-$ decay planes is given by $1+\beta\cos 2\varphi$, where $\beta = -1$ for pseudoscalar X, and $1 \geq \beta \geq 0$ for scalar X.

The state $X(2.85)$ first seen at DORIS[1] may, at last, also have been observed in a hadronic $\pi^- p$ reaction.[2] The properties of the X state remain to this day a mystery. The observed decay into 2γ rules out a spin-1 assignment[3] for the X. The allowed spin-0 assignment leaves open the issue of a scalar versus a pseudoscalar nature under parity.

By obvious analogy with the π^0,[4] it might seem that, short of an actual observation of X into $\pi^+\pi^-$ or K^+K^-, a definitive test of its parity must await a study of its internal conversion into Dalitz pairs.[5] However, we have found, much to our pleasant surprise, that Yang's parity test,[4] when applied to the decay sequence

$$X \to 2\ (\text{vector mesons}) \to 2\ (\text{boson pairs}),$$

unlike the case with fermion pairs, leads to maximal parity signatures. If $X \to \varphi\varphi$ decay exists, then the correlation function for the azimuthal angle between the two $\varphi \to K^+K^-$ decay planes is given by

$$1+\beta\cos 2\phi, \tag{1}$$

with

$$\beta = -1 \text{ for pseudoscalar } X \tag{2}$$

and

$$1 \geq \beta \geq 0 \text{ for scalar } X, \tag{3}$$

in the boson case. For comparison, the result for the sequence $X \to \varphi\varphi \to 2(e\bar{e})$ is[6]

$$\beta = -0.25 \text{ for pseudoscalar } X \tag{4}$$

and

$$0.25 \geq \beta \geq 0 \text{ for scalar } X, \tag{5}$$

in the fermion case. A signature as maximal as that given by Eq. (2) should help considerably toward confirming the belief among some that X is a pseudoscalar state.

The parity test discussed above applies, of course, to any spin-0 meson that is heavy enough to be able to decay into two φ mesons. Yang's original test involved the 2γ decay mode, with the γ converting into e^+e^- in the presence of an external nucleus. The resulting coefficient β turned out to be small. With the internal Dalitz-pair conversion, however, β became as large as ± 0.48, although the absolute rate has become low. Our main point here is that with the discovery of a whole new generation of spin-0 mesons with mass >2 GeV, a clean experimental signature of their parity nature is available. Since the $\varphi\varphi$ decay into two K^+ and two K^- has the least background, it would be the cleanest decay channel for a parity determination. In principle, the $\rho\rho$, the $\omega\omega$, and even the two-J/ψ channel (if mass is high enough) are also good decay channels to study.

Possible candidates for spin-0 mesons to which this test can be applied are, besides the $X(2.85)$, the 3.455 state in ψ' decay, and the η_c and η_c' mesons. Presumably, if the Υ family is a heavy-quark family modeled after the psion family, there will be spin-0 mesons whose parity can again be experimentally determined.

The signature in the scalar case is not definite because parity alone does not lead to a unique coupling for $X\to\varphi\varphi$, and for φ there is no compelling gauge-invariance requirement. The results in Eqs. (3) and (5) came from a study of the bounds over *all* possible Lorentz-invariant, parity-conserving, time-reversal-invariant couplings.[7]

The most general matrix element for $X\to\varphi(P)+\varphi(k)$ in the scalar case, consistent with these requirements, is given by

$$g\epsilon_\mu^*(P)\epsilon_\nu(K)[\lambda P\cdot K\,\delta_{\mu\nu}-K_\mu P_\nu],$$

with g and λ real. The bounds in Eqs. (3) and (5) come from allowing λ to range from $-\infty$ to $+\infty$.[7]

If, nevertheless, a manifestly gauge-invariant coupling,

$$X(\partial_\mu\varphi_\nu-\partial_\nu\varphi_\mu)(\partial_\mu\varphi_\nu-\partial_\nu\varphi_\mu), \tag{6}$$

is used, and success of the vector-dominance model would encourage us to consider it, then the result for β is very close to its upper bound. For scalar X in the boson case we obtain

$$\beta=\frac{(M^2-2m^2)^2}{(M^2-2m^2)^2+2m^4}, \tag{7}$$

and for scalar X in the fermion case we obtain

$$\beta=\frac{(M^2-2m^2)^2}{(M^2-2m^2)^2+2m^4}\,\frac{(m^2-4\mu^2)^2}{(2m^2+4\mu^2)^2},$$

where M is the mass of X, m is the mass of φ, and μ is the mass of the final fermion. Numerically,

$$\beta=0.944 \text{ for scalar } X(2.85)$$

in the boson case, and

$$\beta=0.236 \text{ for scalar } X(2.85)$$

in the fermion case.

The upper bounds for β in the case of a scalar X (i.e., $+1$ for final boson pairs, $+0.25$ for decay into massless fermion pairs) are obtained by an interaction which completely decouples the zero-helicity states of the massive φ meson from the X.[8] Since for massless vector mesons this is what is forced by gauge invariance, it is clear therefore why a gauge-invariant coupling [Eq. (6)] almost saturates the bound.

For our parity test to be feasible, a prime requirement is that the branching ratio for $X\to\varphi\varphi$ be not negligible against the 2γ mode. In a charmonium picture,[9] where X is identified with a $c\bar{c}$ bound state, the two-gluon annihilation process leads to an estimated 5.9-MeV total width.[10] The final states allowed by the quark-line rule[11] include the $\varphi\varphi$ channel. Indeed, based on the idea that gluons couple universally to all flavors, we can easily derive that in the η_c decay into two vector mesons, the following relation holds:

$$\varphi\varphi:\rho^0\rho^0:\omega\omega:K^{*0}\bar{K}^{*0}=1:1:1:2.$$

These arguments only indicate that the $\varphi\varphi$ channel is not a forbidden nor a suppressed channel. The real reason why we were motivated to study it is the search for an X signal in the recent $\pi^-p\to\varphi\varphi n$ experiment[12] performed by Etkin *et al.* Our point here is that the exceptional signature of its pseudoscalar nature warrants a careful search for this mode. A definitive determination of the intrinsic parity of X obviously has fundamental implications for the entire psion family.[13]

Finally we close with a brief explanation of why the fermion case does not provide a striking signature of the parity. It is simplest to view the decay from the rest frame of one of the vector mesons. For a pseudoscalar X, the decay matrix element vanishes when the polarization vectors of the two φ mesons are parallel. Boson current couples only to polarization vectors in the plane of the decay products. When the two decay planes coincide ($\phi = 0$), the two polarization vectors are coplanar, and so the total decay distribution vanishes. The Dirac current can couple to polarization vectors transverse to the decay plane. Therefore, when the two fermion decay planes coincide, the two polarization vectors do not have to be parallel and the total decay distribution no longer vanishes.

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